Top Mass Measurements at CDF

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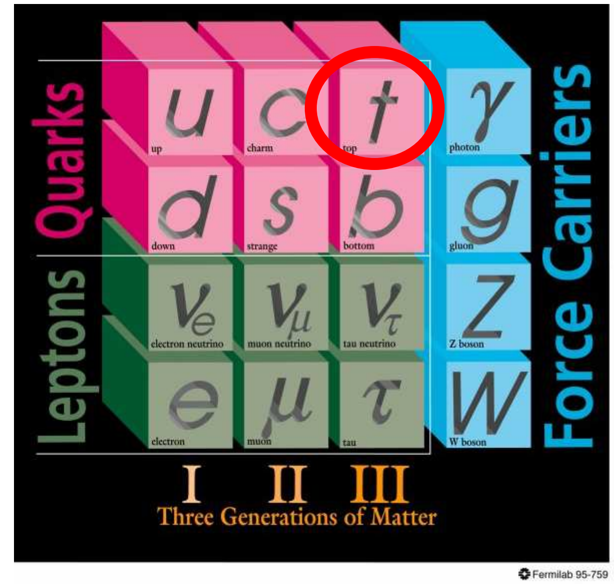
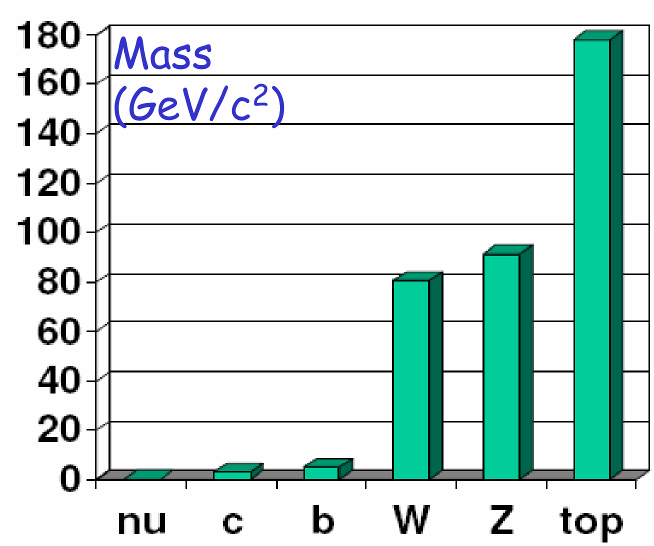
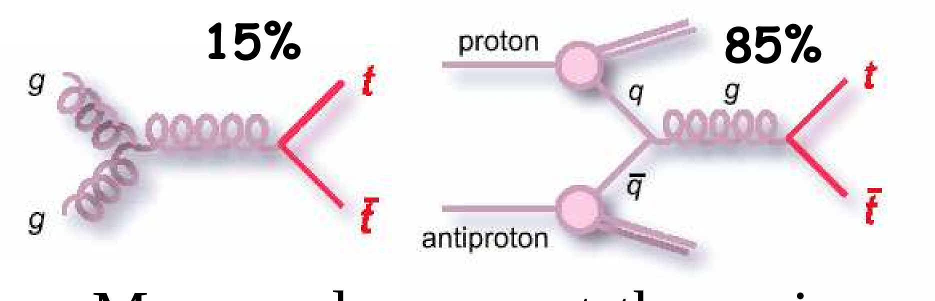
The Top Quark

- Feels strong, electroweak, gravitational forces.
- Short-lived—doesn't hadronize ($\tau=5\times10^{-25}$ s).
- Especially interesting due to its mass
  - Most massive particle at ~175 GeV/c^2.
  - More massive than b quark by factor of 40.
- Studied directly only at the Tevatron.

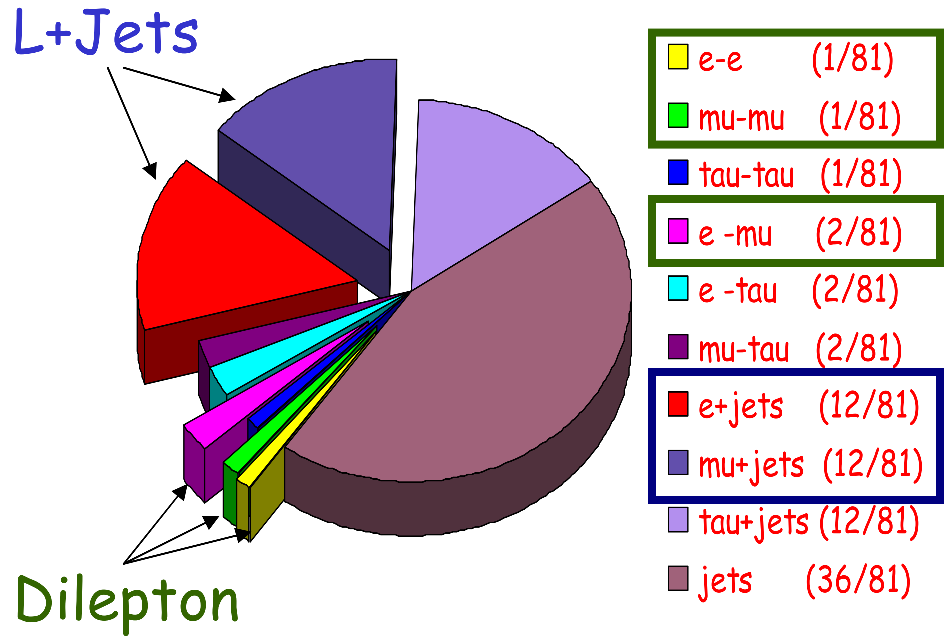


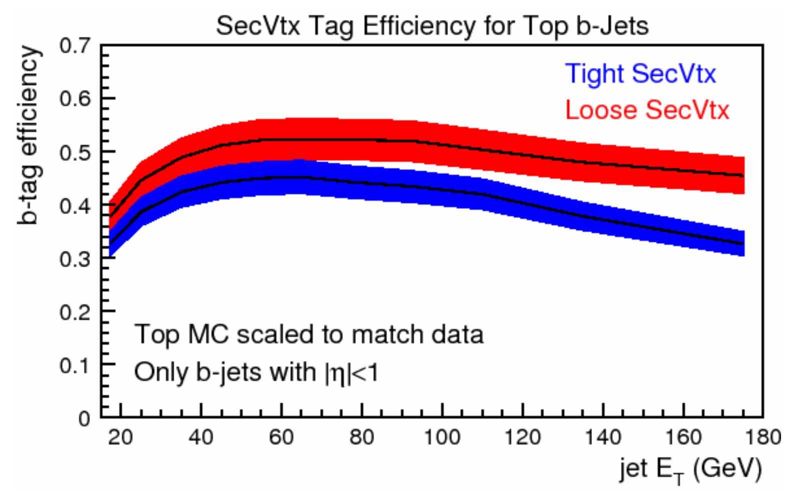


Top Production, Decay, Selection



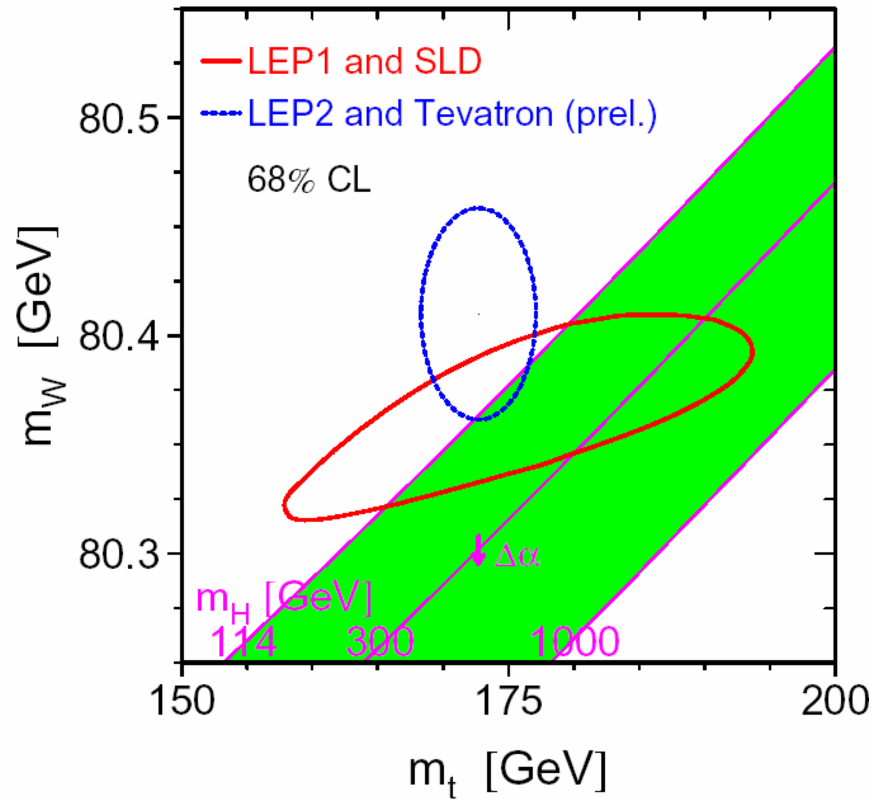
- Mass analyses use t-tbar pairs produced strongly.
  - ~85% quark annihilation, ~15% gluon fusion.
- Top always decays to W boson and b quark.
  - Events classified by decay of W to leptons or quarks
    - Dilepton: 2*e|μ, MET, 2 jt
    - L+jets: e|μ,MET,4 jt
    - All-hadronic: 6 jt
- B tagging (displaced vertex) improves S/B ratio.





Why Measure the Top Quark Mass?

- Fundamental parameter of Standard Model.
  - Unexpectedly large: m_b x 40
- Related through radiative corrections to other EW observables.
  - Very important for precision tests of SM.
  - With m_W, constrains m_H.
- SM Yukawa coupling ~ 1 → Special role in EWSB??

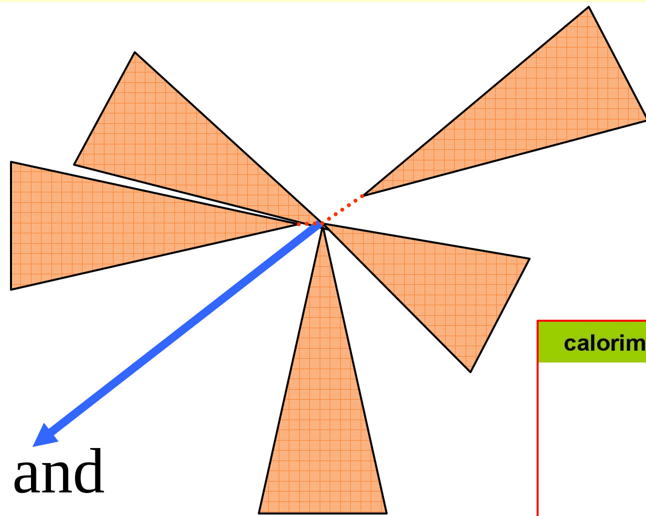


$$M_t = \frac{1}{\sqrt{2}} \lambda_t v$$

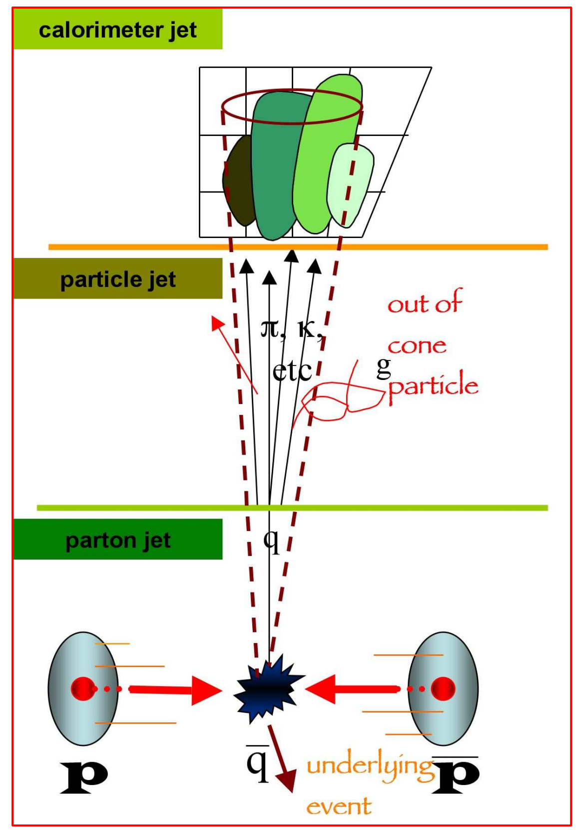
$$\Rightarrow \lambda_t = \frac{M_t}{173.9\,\mathrm{GeV}/c^2}$$

A Difficult Measurement

- Complicated events
  - Only ~50% of l+jets events have leading 4 jets from tt decay.
  - 12 ways to interpret 4 jets ↔ 4 partons.



- Jet energy resolution effect and jet energy scale systematics
  - Resolution $85\%/\sqrt{E_T} \rightarrow$ statistical uncertainty.
  - Systematic $3\% \rightarrow$ systematic uncertainty.
- Background contamination
  - Well understood S:B of 1:1–10:1.
  - Must be treated properly to avoid bias.
- Run IIa goal for M_{top} (2 fb^{-1})
  - CDF: 3 GeV/c^2 precision
  - Tevatron: 2 GeV/c^2 precision

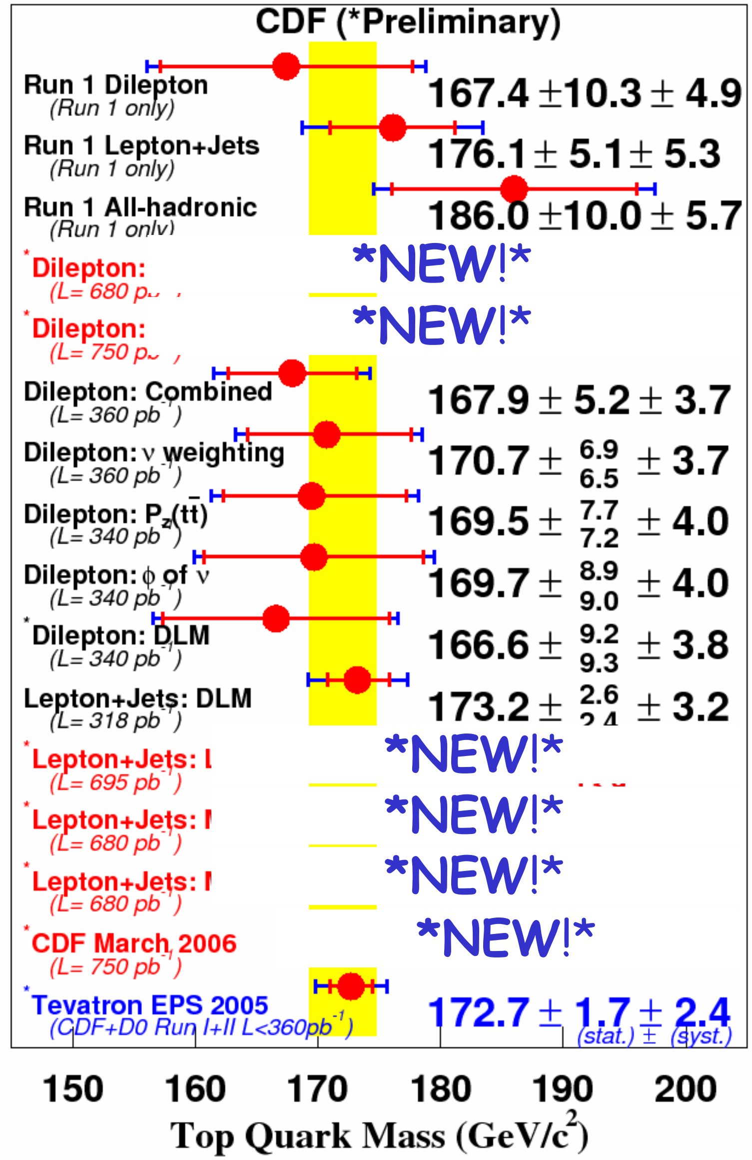


Top Mass at CDF

- Robust program of top mass measurements
- Good statistics → precision measurements
- Many analysis techniques with different sensitivities → high confidence
- **Five new results using 680-750 pb^{-1}.**

Events (S+B) in 680-750 pb^{-1}

	Pretag	≥1 b tag	2 b tags
Dilepton	64	27	7
Lepton + Jets	360	252	57
All-hadronic		O(600)	



How to Weigh Truth

TEMPLATES

1. Pick a kinematic observable (e.g. reconstructed mass).
2. Create "templates" using events simulated with different M_{top} values (+ background).
3. Perform maximum likelihood fit to extract measured mass.

Kinematic information

MATRIX ELEMENT

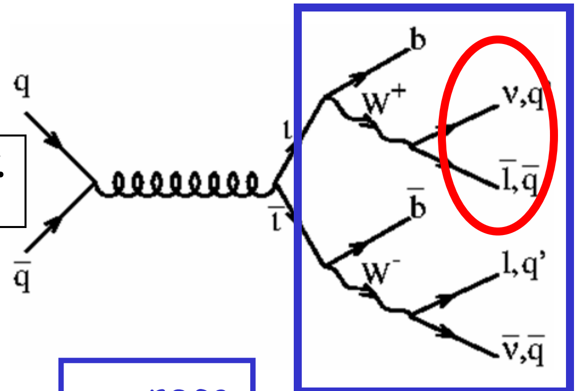
1. Build likelihood directly from PDFs, matrix element(s), and transfer functions that connect quarks and jets.
2. Integrate over unmeasured quantities (e.g. quark energies).
3. Calibrate measured mass and error using simulation.

+ Dynamical information

Both techniques rely on good Monte Carlo and detector simulation!

Template Analysis (L+Jets) Overview

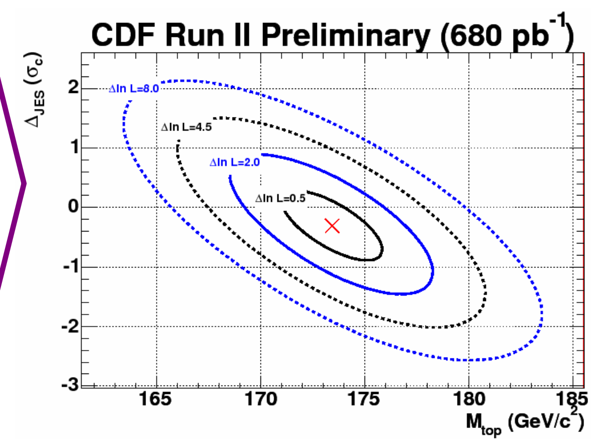
$q\bar{q} \rightarrow t\bar{t}$



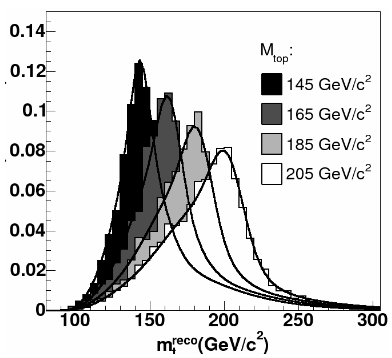
- Kinematic fit to reconstruct top quark mass in each event
- Invariant mass of possible W decay jets

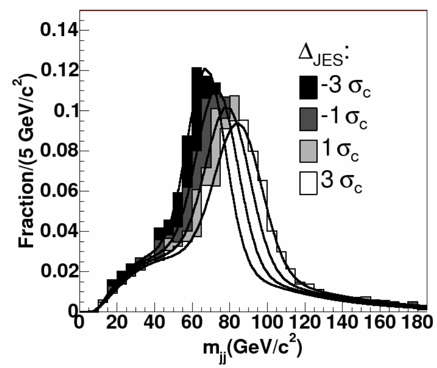
Observables: m_t^{reco}, m_{jj}

Parameters: M_{top}, Δ_{JES}



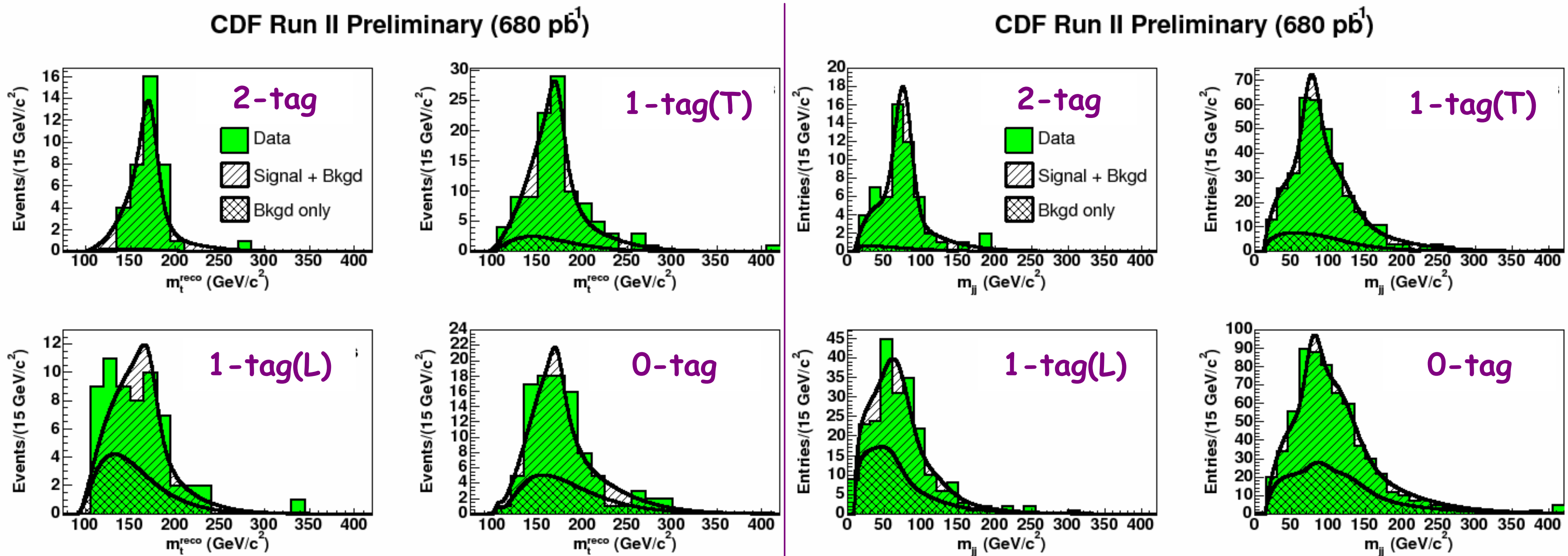
This method, 318 pb^{-1}:
PRL 96, 022004;
PRD 72, 032003





- Δ_{JES}: deviation from nominal in units of external calib.
- Ext. max. likelihood using 4 subsamples; constrain $\Delta_{JES} = 0 \pm 1\ \sigma_c$

Template (L+Jets) Results—680 pb^{-1}



m_t^{reco} in data w/ fit overlaid

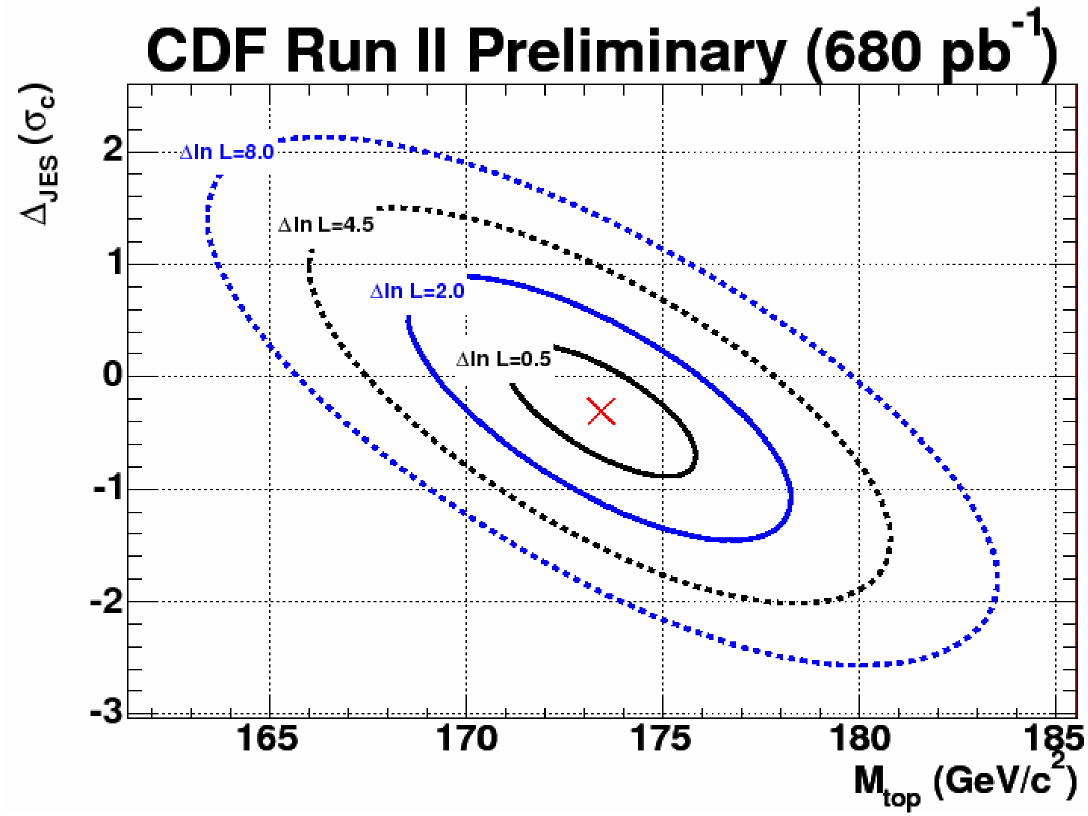
m_{jj} in data w/ fit overlaid

$\Delta_{JES} = -0.3 \pm 0.6$ (stat. + M_{top}) σ_c

40% improvement in dominant JES systematic!

Template (L+Jets) Results—680 pb^{-1}

Likelihood contours in M_{top}-Δ_{JES} plane



Systematic	ΔM_{top} (GeV/c^2)
Residual JES	0.7
B-jet energy scale	0.6
Bkgd JES	0.4
Bkgd Shape	0.5
ISR	0.5
FSR	0.2
Generators	0.3
PDFs	0.3
MC stats	0.3
B-tagging	0.1
TOTAL	**1.3**

$$M_{top} = 173.4 \pm 2.5\,(\mathrm{stat}) \pm 1.3\,(\mathrm{syst})\,\mathrm{GeV}/c^2$$

Matrix Element (L+Jets) Overview

New method for 680 pb^{-1} dataset!

Dynamical Likelihood Method (different ME analysis), 318 pb^{-1}:

PRL 96, 022004; hep-ex/0512009

- Likelihood simultaneously determines M_{top}, Jet Energy Scale, and signal fraction

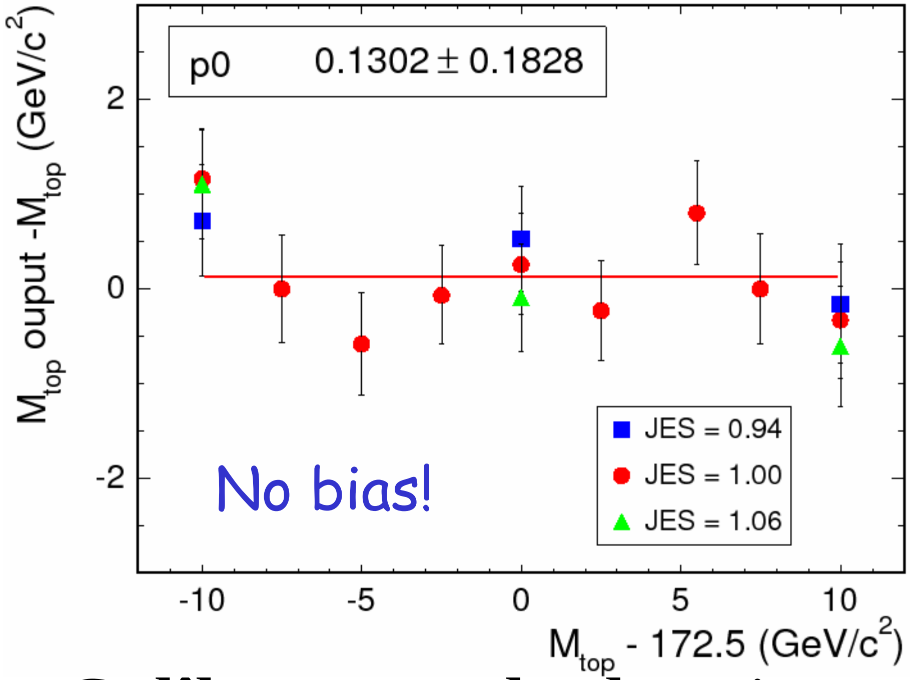
$$P_o(\vec{x}; m_t, JES, c_s) \equiv c_s P_{t\bar{t}}(\vec{x}; m_t, JES) + (1 - c_s) P_{W+jet}(\vec{x}; JES)$$

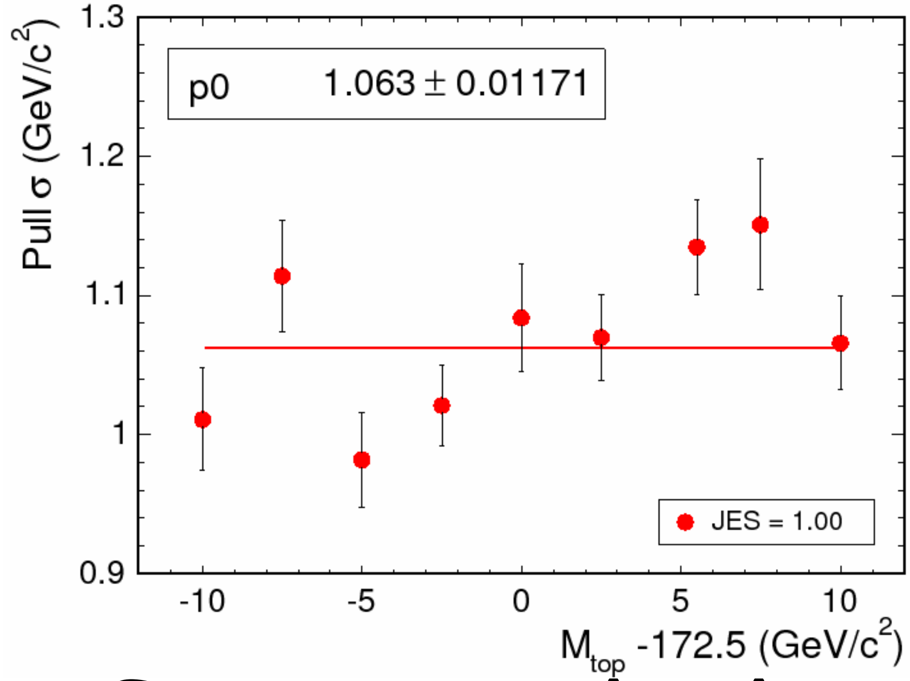
- Probabilities built from matrix element, transfer functions, and parton distribution functions

$$P_{t\bar{t}}(\vec{x}; m_t, JES) = \frac{1}{\sigma} \int d\sigma_{t\bar{t}}(\vec{y}; m_t) dq_1 dq_2 f(q_1) f(q_2) W(\vec{x}, \vec{y}, JES)$$

- JES sensitivity comes from W resonance.
- Uses kinematic & dynamical features of each event.
- All jet-parton assignments are considered, weighted.
- Select events with exactly 4 jets, well described by LO ME.
  - Require b tag to improve sample purity.

Matrix Element (L+jets) Technique



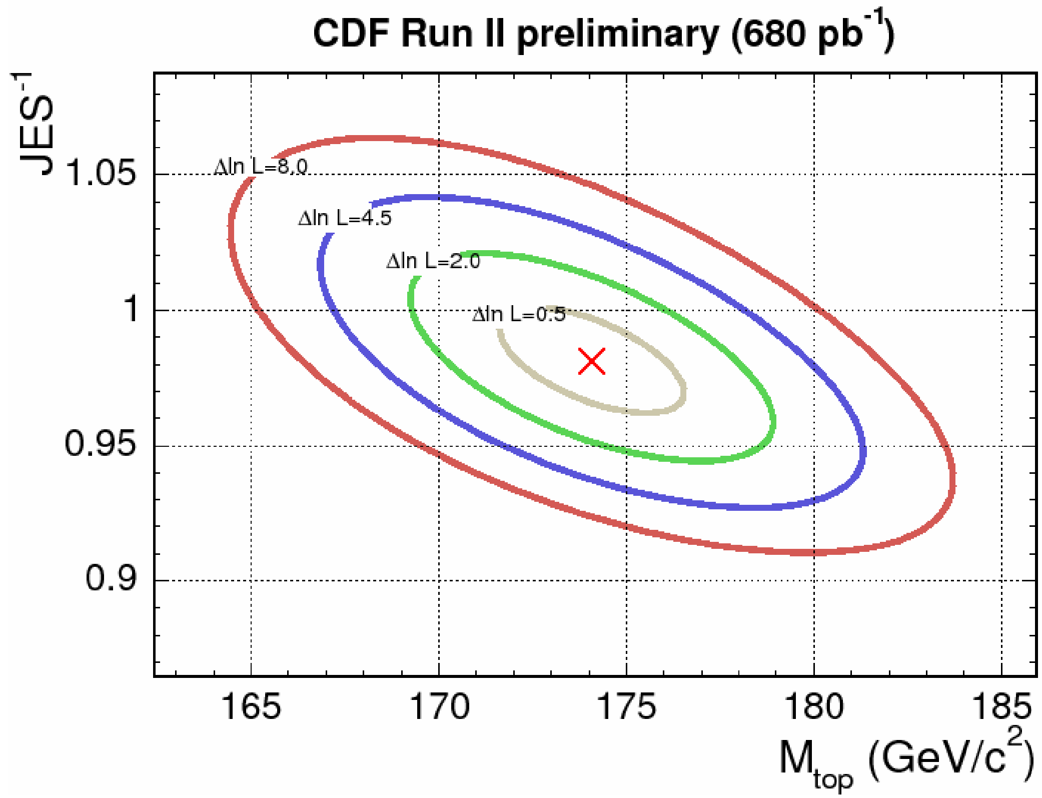


- **Calibrate method** against MC samples.
  - Shows **unbiased** measurement.
  - Errors rescaled to account for observed pull width.
- Corrects **approximations** in integration:
  - Angles perfectly measured
  - Lepton energy perfectly measured
  - Jets are from ttbar decay

Matrix Element (LJ) Results—680 pb^{-1}

- JES here is constant multiplicative factor.
  - $E^{data} = E^{MC}/JES$
- JES = 1.02 ± 0.02.
  - Very close to central value of template method

Systematic	ΔM_{top} (GeV/c^2)
Add'l JES	0.7
Signal Modeling	1.1
Other	0.4
TOTAL	**1.4**



Virtually identical sensitivity with fewer events!

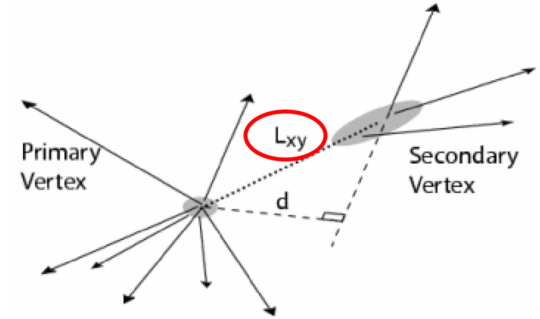
$$M_{top} = 174.1 \pm 2.5\,(\text{stat}) \pm 1.4\,(\text{syst})\,\text{GeV}/c^2$$

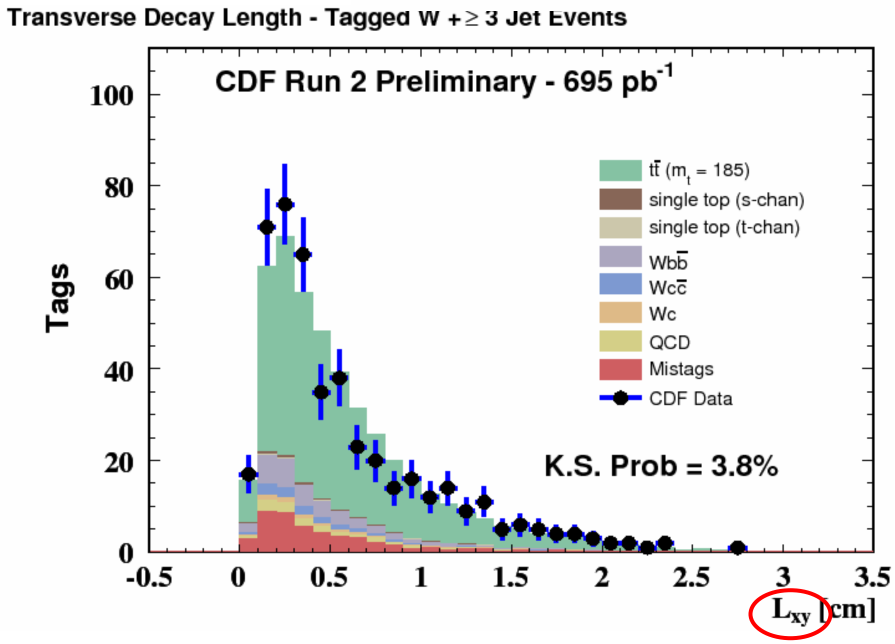
Decay Length Technique—680 pb^{-1}

- B hadron decay length ∝ b-jet boost ∝ M_{top}
- Difficult template analysis—measure slope of exponential.
- But systematics are dominated by tracking effects

  → Small correlation with traditional measurements!
- So far: L+jets channel, but extended acceptance—not limited to 4-jet events.
  - 375 events
- Statistics limited now
  - Can make significant contribution at LHC

Method:
PRD 71, 054029

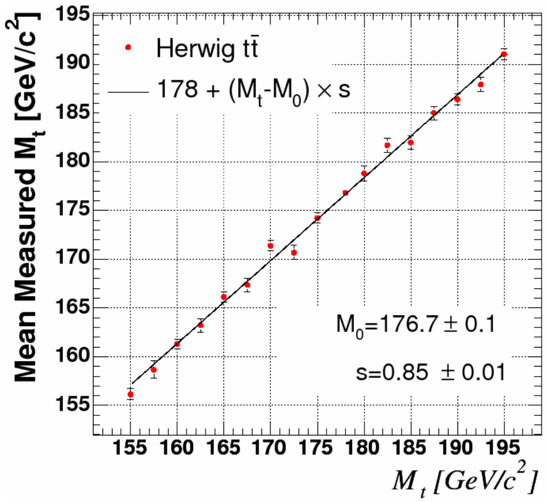


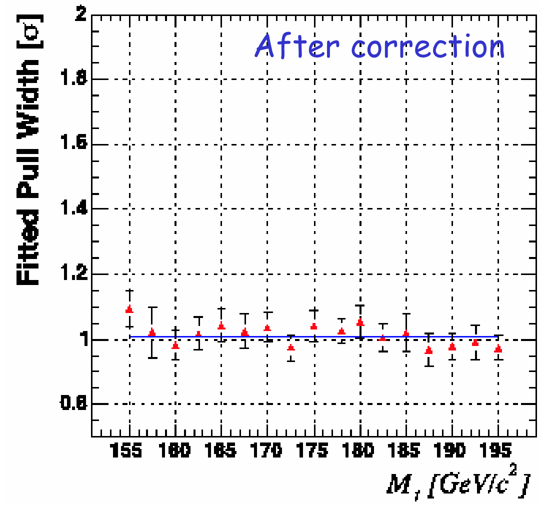


$$M_{top} = 183.9^{+15.7}_{-13.9}\,(\text{stat}) \pm 5.6\,(\text{syst})\ \text{GeV}/c^2$$

Matrix Element (Dilepton) Technique

- Harder to reconstruct M_{top} in dilepton events: two neutrinos make system underconstrained.
  - More amenable to ME approach
- Likelihood is similar to L+jets.
  - No W resonance $\rightarrow$ no fit for JES
  - Add ME for dominant bkgds: DY+jets, WW+jets, fakes
- Approximations have significant effect
  - MC calibration essential
  - Correct fitted mass for calibration slope of 0.85
  - Correct for pull width of 1.49 (constant in M_{top})
- Analysis performed also on tagged subsample.





	Events	S:B
≥0 b tags	64	~2:1
≥1 b tags	27	~20:1

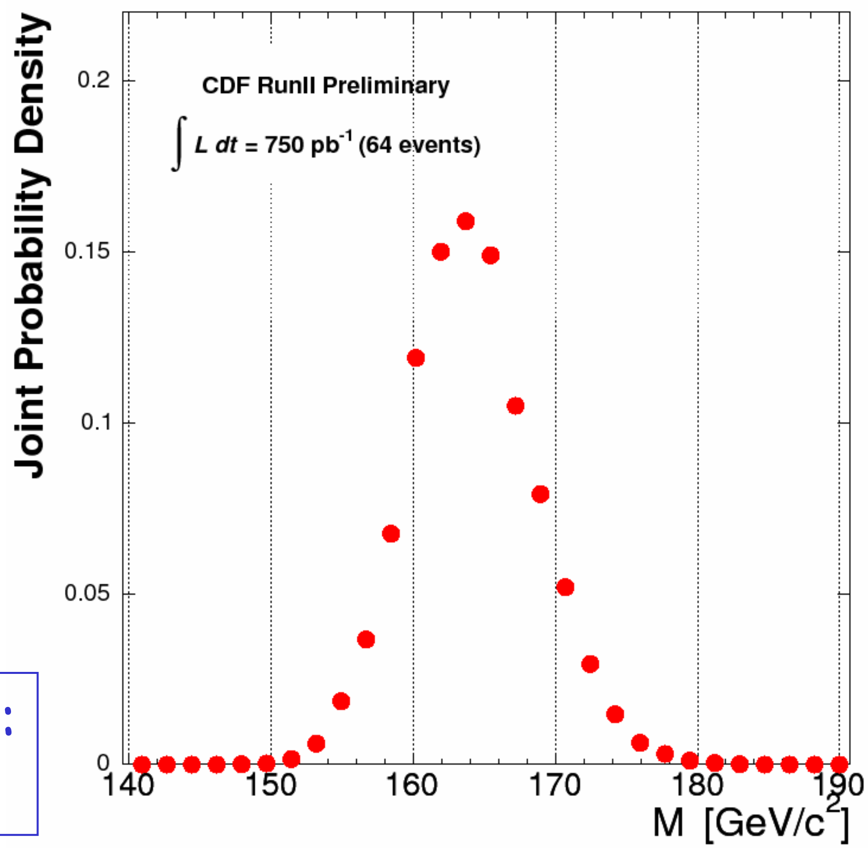
This method, 340 pb^{-1}: hep-ex/0512070

Matrix Element (Dil) Results—750 pb^{-1}

- Best measurement in challenging dilepton channel.
- Could reach 2 GeV (stat) sensitivity by end of run II.

Systematic	ΔM_{top} (GeV/c^2)
JES	2.6
Signal Modeling	1.1
Other	1.3
TOTAL	**3.1**

Restrict sample to b-tagged events:
$M_{top} = 162.7 \pm 4.6 \pm 3.0\ GeV/c^2$

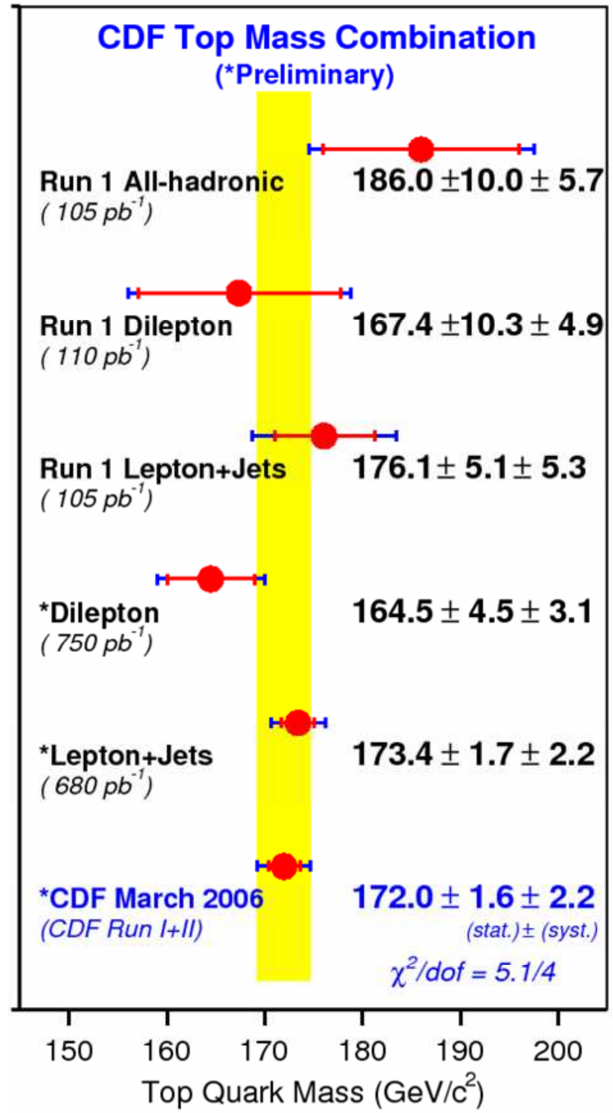


$$M_{top} = 164.5 \pm 4.5\,(\text{stat}) \pm 3.1\,(\text{syst})\,\text{GeV}/c^2$$

Combination of CDF Results

- Use BLUE (Best Linear Unbiased Estimator) technique.
  - *NIM* ***A270*** *110,* ***A500*** *391*.
- Accounts for correlations in systematics.
- Stat correlations in progress.
  - So far only combine measurements on independent datasets (incl run I).

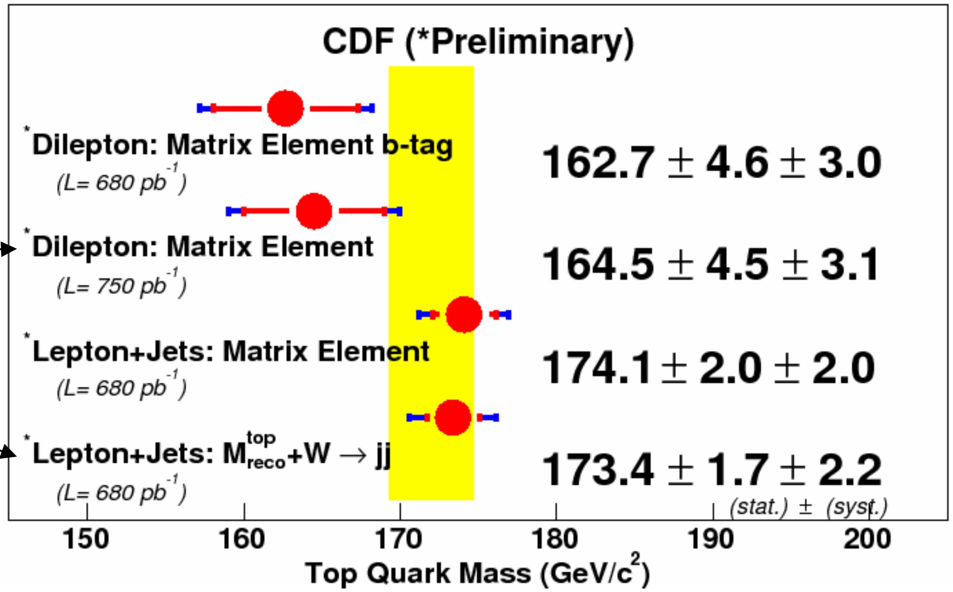
$$M_{\text{top}} = 172.0 \pm 1.6\,(\text{stat}) \pm 2.2\,(\text{syst})$$
$$= 172.0 \pm 2.7\,\text{GeV}/c^2$$
$$\chi^2 = 5.1/4\,(28\%)$$



Updated CDF+D0 combined result coming…

Keep an Eye on This…

- See some discrepancy between L+jets, Dilepton channel M_{top} measurements.
- Statistically consistent so far:
  - ME(dil) vs Templ(L+jets): **χ^2 = 2.9/1, p=0.09**. (Accounts for correlated systematics)
- But what if it persists?
  - Could there be a missing systematic?
    - Would have to affects the channels differently…
  - Could our assumption of SM ttbar be incorrect?
- Will be interesting to see all-hadronic measurements.

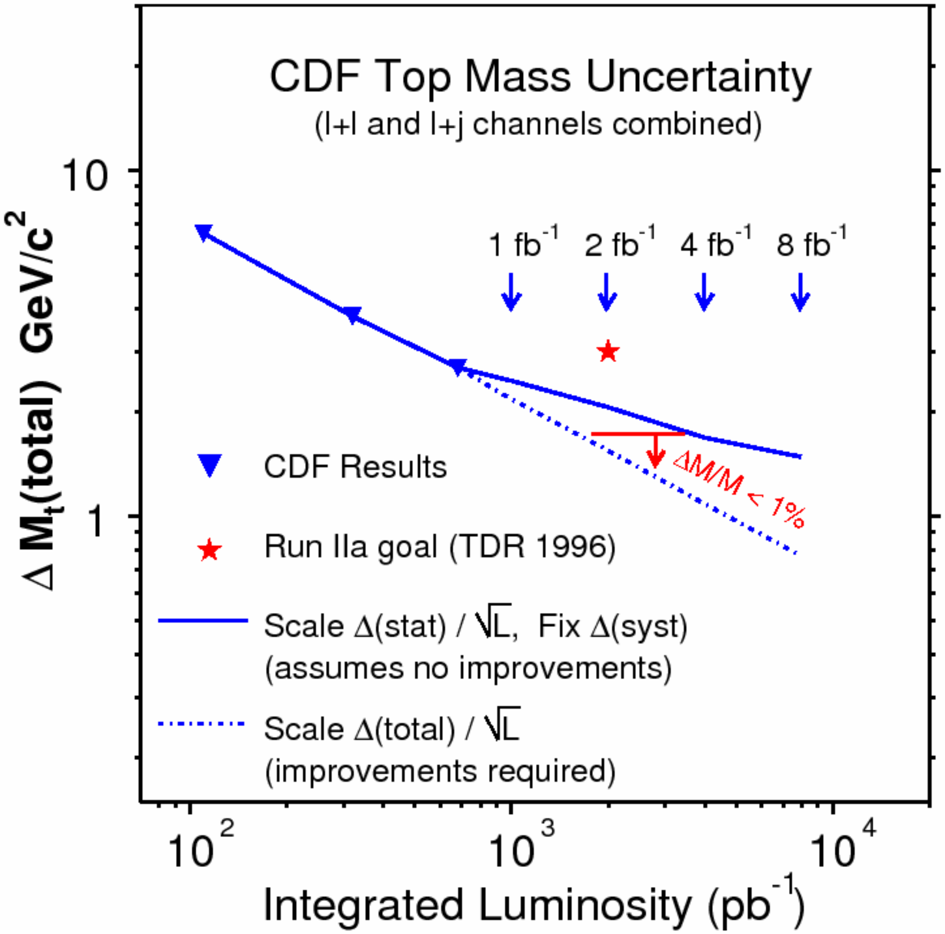


Stay tuned…

Conclusions

$$M_{\text{top}}(\text{CDF}) = 172.0 \pm 2.7\ \text{GeV}/c^2$$

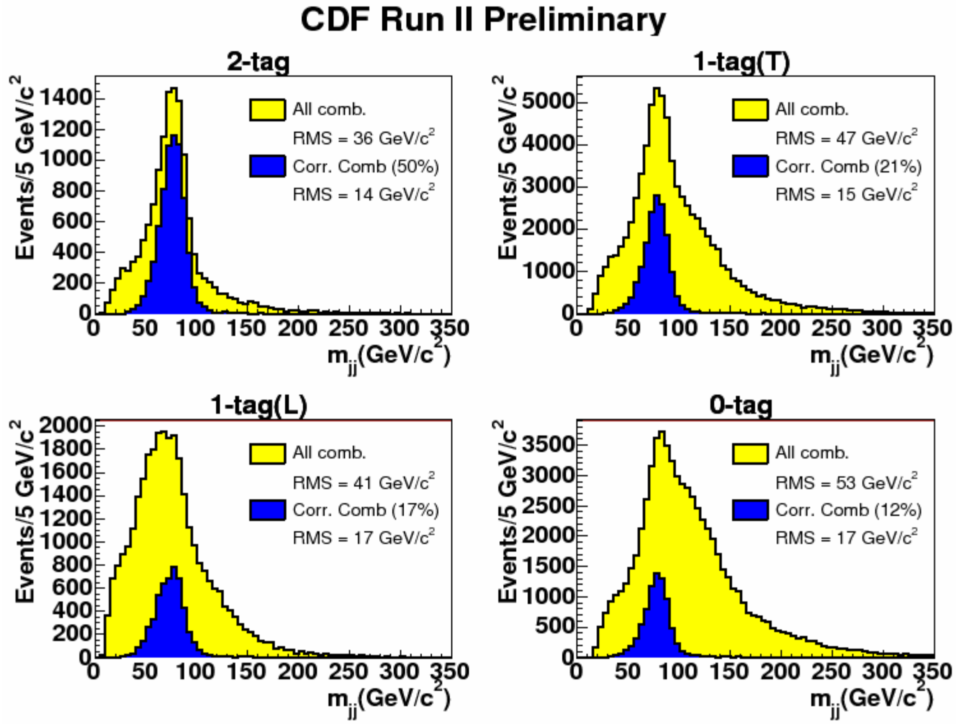
- CDF has surpassed our run IIa goal of 3 GeV/c^2 precision on M_{top}.
  - Goal assumed 2 fb^{-1}!
- With *in situ* JES calibration, dominant "systematic" now scales as 1/sqrt(N).
- 1% uncertainty on M_{top} is in sight as we concentrate on reducing remaining systematics

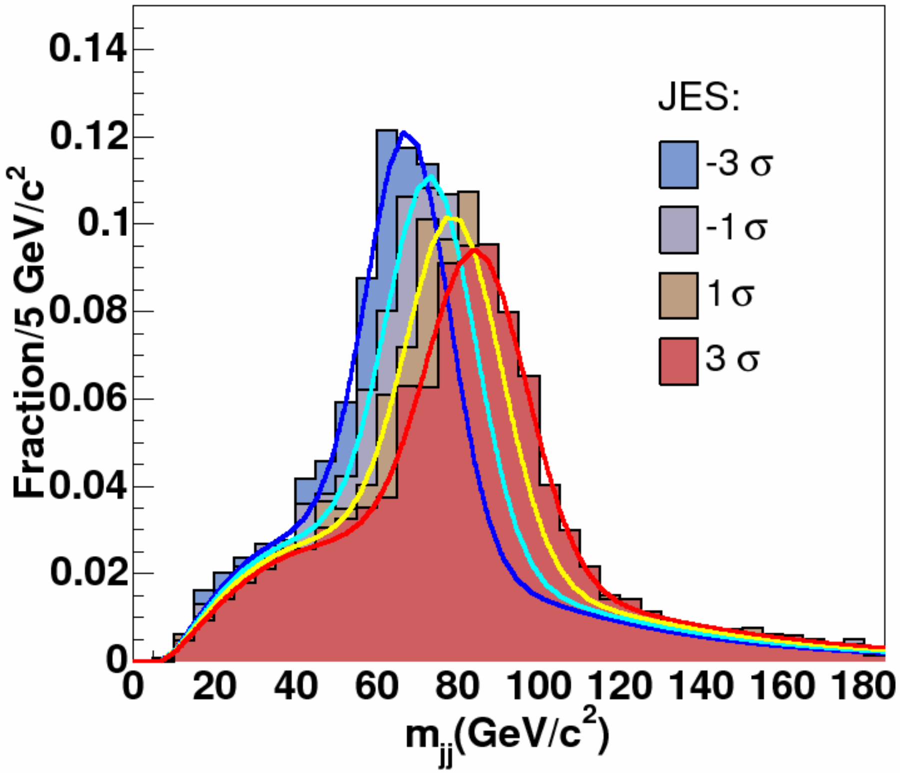


Backup Slides

Measure JES Using Dijet Mass

- Build templates using invariant mass m_{jj} of all non-tagged jet pairs.





- Rather than assuming JES and measuring M_W...
- Assume M_W and measure JES
- Parameterize $P(m_{jj};JES)$ same as $P(m_t^{reco};M_{top})$

Systematics: ISR/FSR/NLO

- Method in hand to use Drell-Yan events to understand and constrain extra jets from ISR.
  - Constraint scales with luminosity.
  - Easily extendible to FSR.
- MC@NLO sample shows no add'l NLO uncertainty is needed.